Wound-Field Synchronous Machine-System Integration toward Increased Power Density and Commercialization

Presenter:
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Project ID #elt252
Date/Time: 6/22/2022
10:00:00 AM EDT

Overview

Project Period (39 months)

Start Date: 2019-Oct

End Date: 2022-Dec

Budget

Total Project Funding	$ 875,000
Cost Incurred thru Feb 2022 (75.6%):	
Magna	$ 423,334
IIT	$ 123,394
UW-Madison	$ 116,496
==	
Cost Incurred thru Feb 2022	$ 661,224

Technology Partners

Magna International Inc. (Recipient)
Illinois Institute of Technology (IIT) (Subrecipient)
University of Wisconsin – Madison (UW) (Subrecipient)

Barriers & Technical Targets

- Develop wound field synchronous motor demonstrating:
  - 8X increase in power density
  - Cost <= $ 3.3/kW

Accomplishments

- Two motor designs have been found to meet the targets
- One commercially feasible motor design has been optimized against electromagnetic, thermal and structural boundary conditions for prototype build
- Hair-pin stator hardware is ready and is being used towards prototype build
- Stator and rotor cooling system architectures have been selected and is currently being optimized for the final prototype build
- Multiple versions of capacitive rotor excitation electronics have been designed, simulated, fabricated and tested
- First version of inductive power transfer system has been designed and will be built

Deliverables

- Dec. 2020 – Preliminary FEA results demonstrating potential of meeting program objectives
- Dec. 2021 – Completion of motor design for manufacturing
- Dec. 2022 – Prototype testing and report generation

Project Objectives

Budget Period 3: January 2022 – December 2022

Task 3.1 – WFSM prototype build for testing

Task 3.2 – Testing of prototype WFSM

Subtask 3.1.1 – Design of baseplate and coupling arrangement to test WFSM system on testbench
Subtask 3.1.2 – Commissioning of stator inverter and rotor excitation inverter
Subtask 3.1.3 – Comprehensive testing of the prototype WFSM system
Subtask 3.1.4 – Comparative analysis and reporting

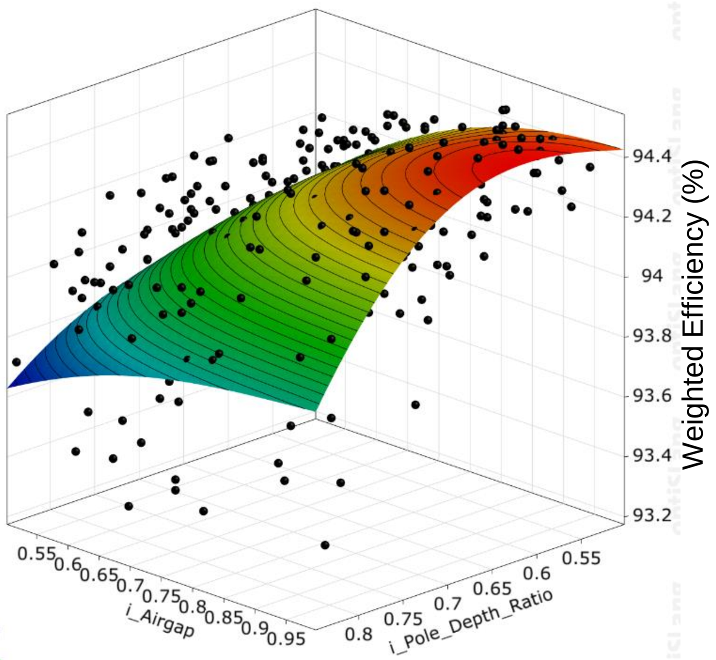
Go/No Go	**Prototype power density >= 50 kW/L and cost <= $3.3/kW**

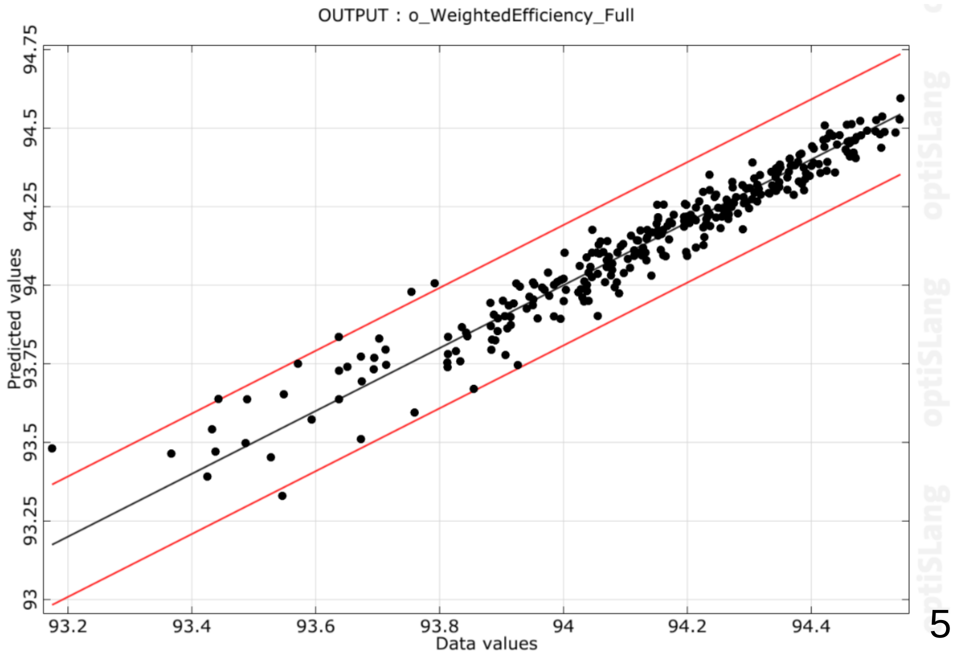
WFSM Design and Optimization Project Accomplishments & Progress

Wound Field Synchronous Machine (WFSM) Optimization

- Direct optimization of WFSMs can take infeasible amounts of time if drive cycle efficiency is to be optimized because of the variable field excitation
- Meta-modeling approach used with custom Python scripting to couple ANSYS optiSLang with Motor-CAD
- Stator and field currents determined to meet desired load points with iterative corrections
- Constraints on current densities, load point torque deviations, terminal voltage at each load point, maximum total rotor loss, and load point torque ripple while maximizing weighted efficiency
- Large number of slot pole combinations and winding technologies explored including custom rotor geometries

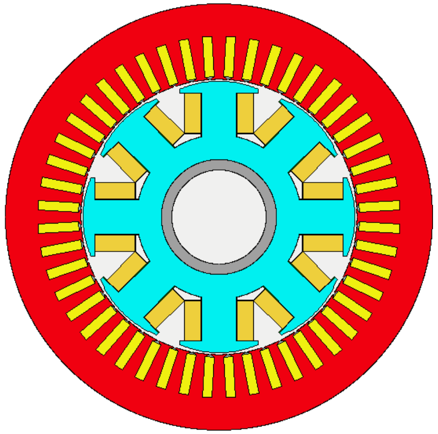
Representative metamodel (MOP) for drive cycle efficiency constructed from 300 sample designs





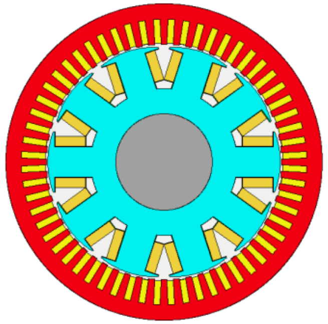
Summary – Initial WFSM Designs

EM – 3.2
Commercially Feasible



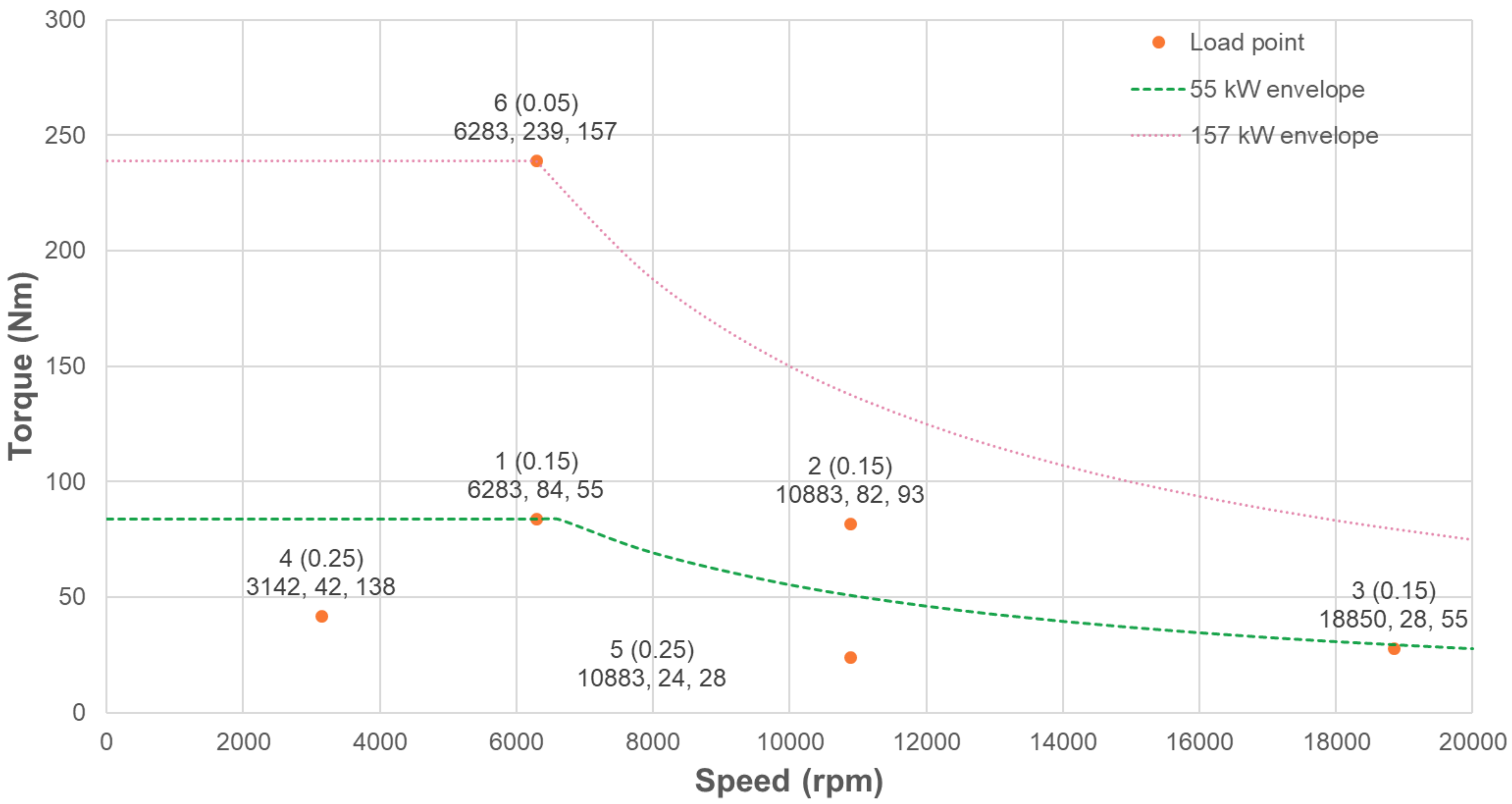
- Based on production stator, custom rotor
- <u>50kW/L active materials, 31kW/L full envelope</u>
- 390 A_{rms}(Inverter)
- 450Vdc –> 157kW, 6283 rpm
- Stress checked to 28,800rpm (w/o dovetails)
- 70% rotor fill - weighted eff. 95.4% (motor only)
- Stator jacket + rotor jets
- 55 mm shaft

EM – 2.0
Manufacturing Challenges/Limitations



- Custom design stator and rotor
- <u>62 kW/L active materials, 50kW/L full envelope</u>
- 390 A_{rms}(Inverter)
- 360Vdc –> 100kW, 8000 rpm
- Stress checked to 28,800rpm (w/o dovetails)
- 72% rotor fill - weighted eff. 94.77% (motor only)
- Stator jacket + rotor jets
- 36.5 mm shaft

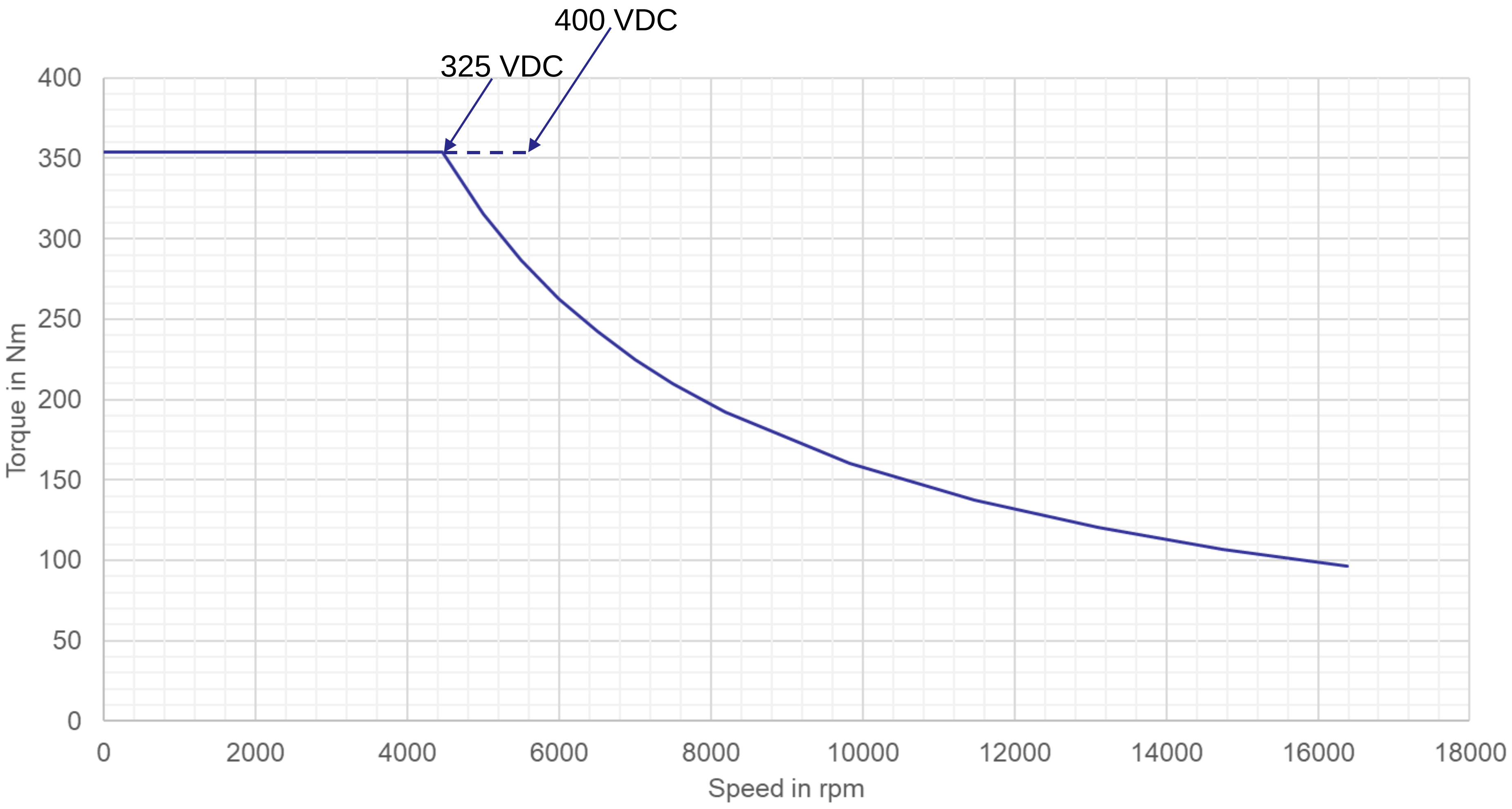
Optimization load points for EM 3.2 @ 450VDC



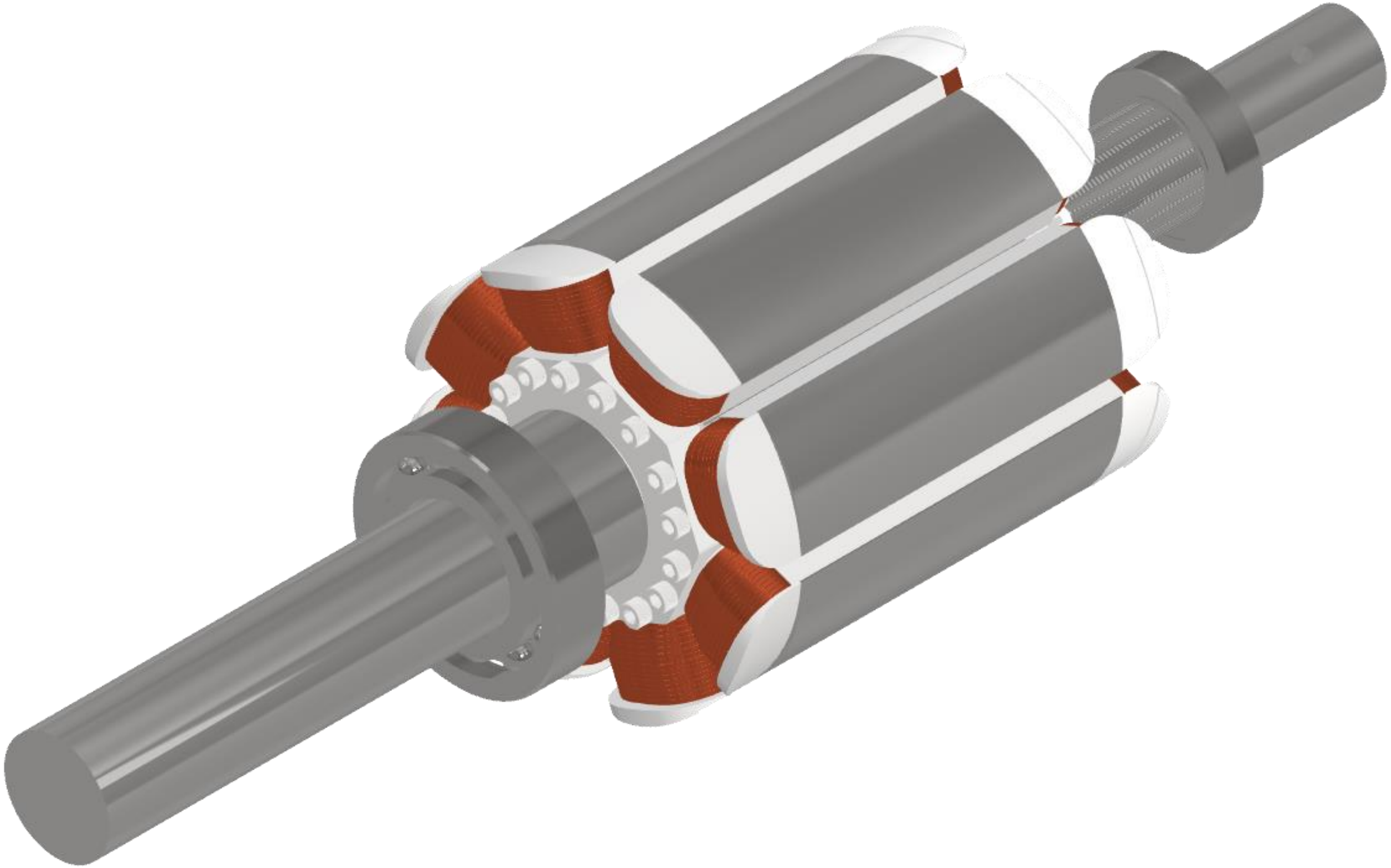
Final Prototype Design Optimization

- EM 3.2 design revised/re-optimized based on a Magna hairpin stator in serial production
- Combined magnetic and structural optimization
  - Maximize weighted efficiency subject to current density, torque ripple, voltage, and Von Mises stress constraints
- New operating space map with 10 load points
- Designed to achieve a 50 kW/L active power density
  - Design can reach this power density
- Predicted weighted efficiency of the machine 95.89%
  - Includes full stator DC+AC ohmic loss, field ohmic loss, and all iron losses

Torque-Speed Envelope of the Final Prototype Design

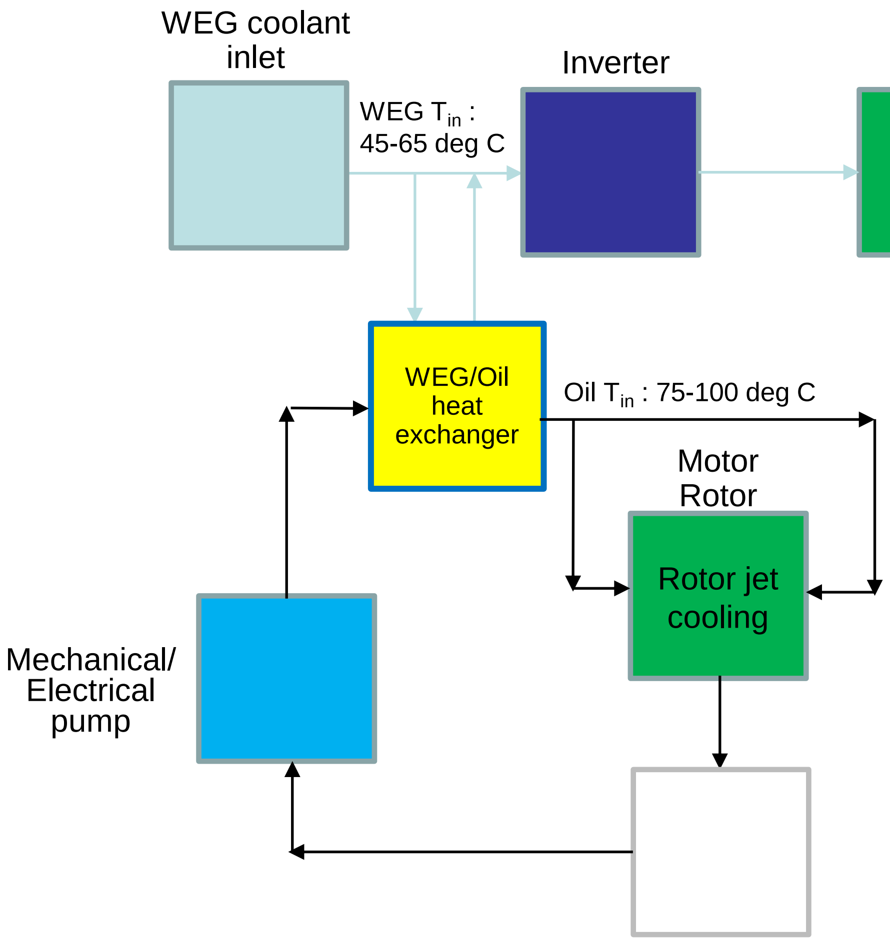


Final Prototype Rotor Design

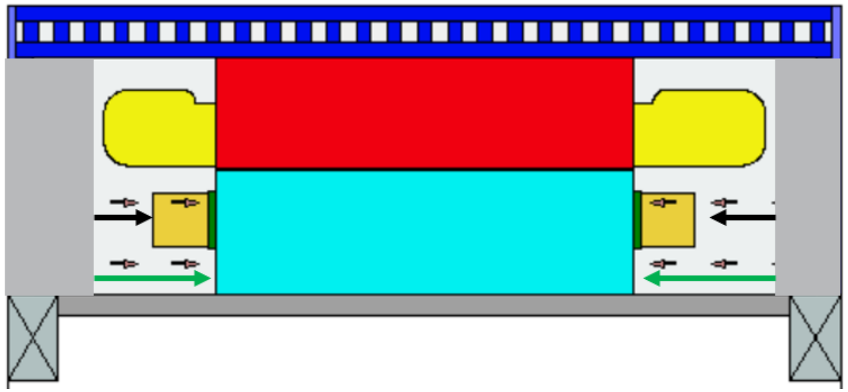


Cooling System Design and Optimization Project Accomplishments & Progress

Motor Cooling Architecture



Architecture selected for optimization

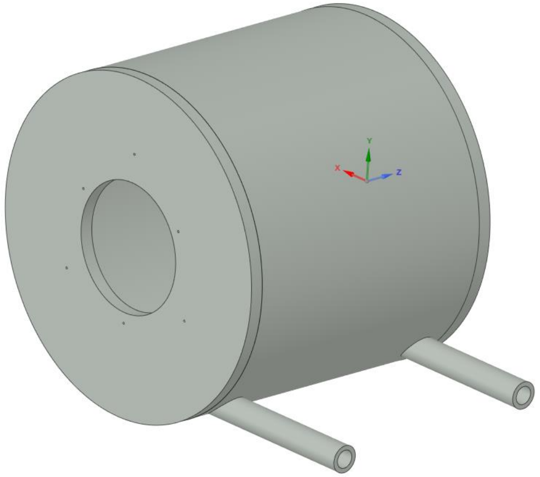


- Several liquid cooling architectures investigated
- Water Ethylene Glycol (WEG) used for stator cooling
- Oil used for rotor cooling
- Oil flow rate investigated: 1L/min to 12 L/min
- WEG flow rate investigated: 4L/min to 12L/min
- Oil inlet temperatures investigated: 75 deg C to 100 deg C
- WEG temperatures investigated: 45 deg C to 65 deg C

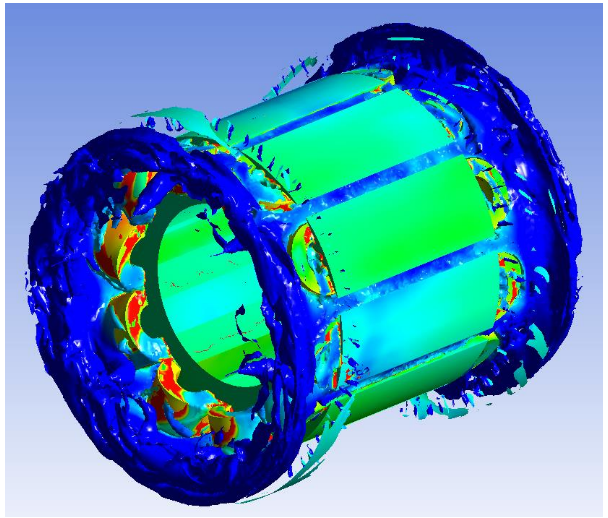
Selected Cooling System Design for Prototype

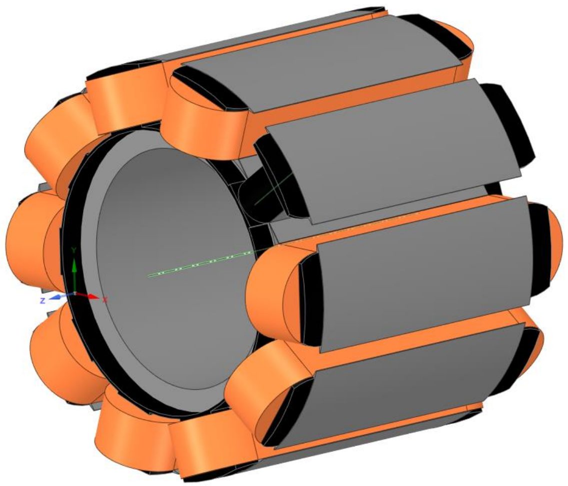
- Spiral water jacket was selected for stator cooling
- Oil jet impingement from the axial ends was selected for rotor cooling
- Various rotor jet parameters were investigated such as number of jets, location, spacing, nozzle dimension, etc.
- Speed of the rotor influences cooling performance – Higher speed leads to better heat transfer
- High speed of rotor also calls for very low flow rate and high temperature of oil

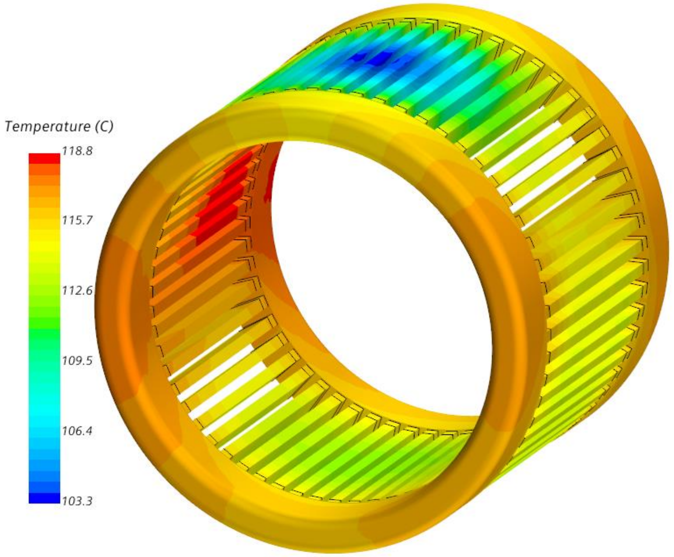
Axial jets meaning from the end-plates



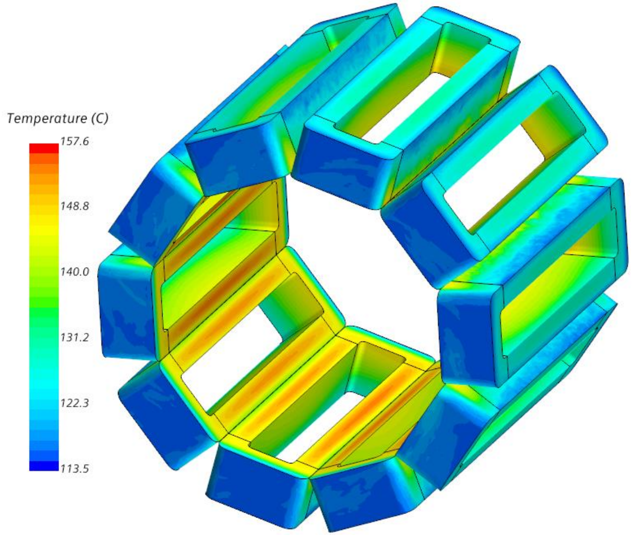
CFD simulations with splashing and coil carrier for temperature prediction and drag losses







Max. stator temp – 118 deg C @ 75 deg C, 8L/min WEG



Max. rotor temp – 157 deg C @ 100 deg C oil, 1.6 L/min

Rotor Excitation System Design and Optimization
Project Accomplishments & Progress

Excitation System Summary

Summary:

Successful development of 6.78MHz GaN inverter for CPT

- Identification and elimination of ringing
- Deadtime down to 12ns
- Tested output power to 100’s of Watts to 1 kW peak. Inverter efficiency ~99%
    - DC – DC efficiency limited by high frequency tank ESR and rotor diode loss. 91% peak.
    - Loss too great to practically scale >3kW throughput field power.

Conclusions:

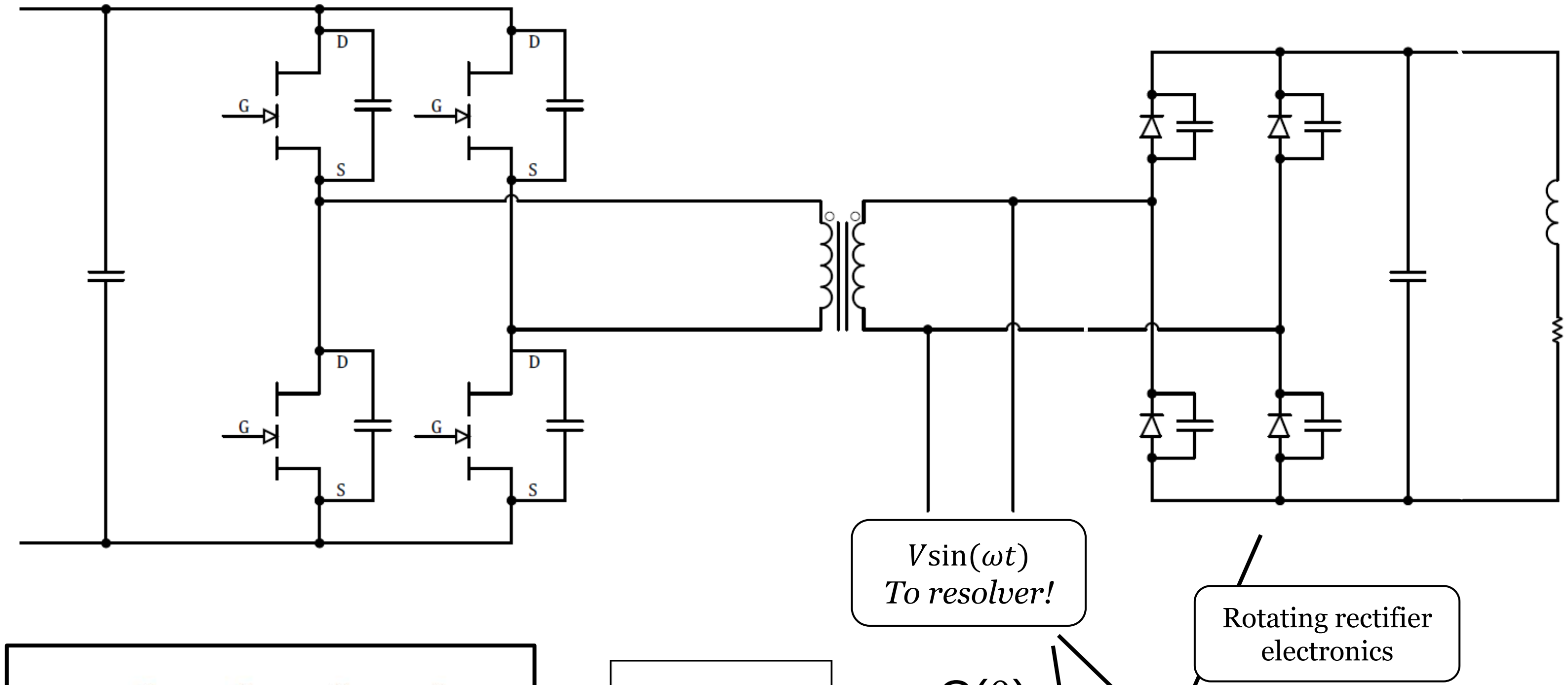
ISM band Capacitive Power Transfer (CPT) works well for motors with < 1.5 kW peak field power

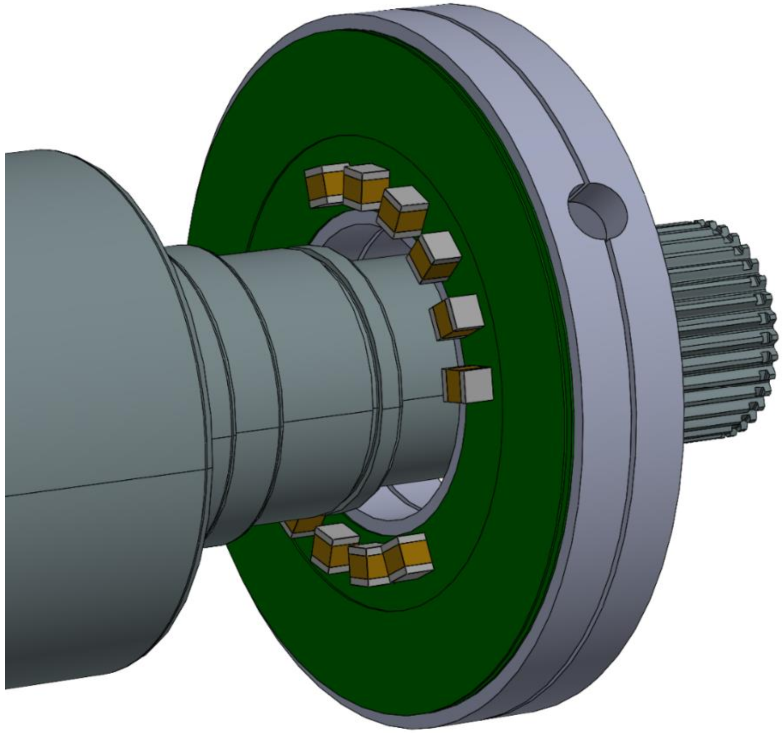
- More development to achieve success for motors with >1kW and multi-kW peak field power
- ISM band Capacitive Power Transfer could be paired with a 10-20kW WFSM.
    - e.g. a 10kW WFSM would require ~250W peak field power assuming a high slot fill factor.
- ISM band Capacitive Power Transfer is relatively low cost and straight forward.
    - Could even go with a class E driver (single switch)

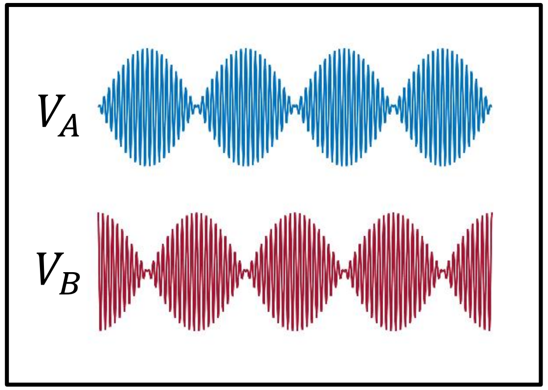
Suggested path forward for this DOE project:

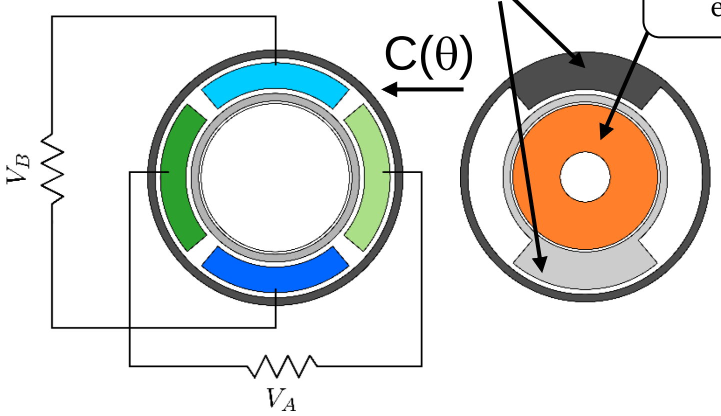
Utilize a gapped transformer, Inductive Power Transfer (IPT) approach with the GaN inverter operating in the 25 kHz to 100 kHz range. Can integrate capacitive resolver into rectifier board for “free.”

Increasing Field Power Requirements lead to IPT





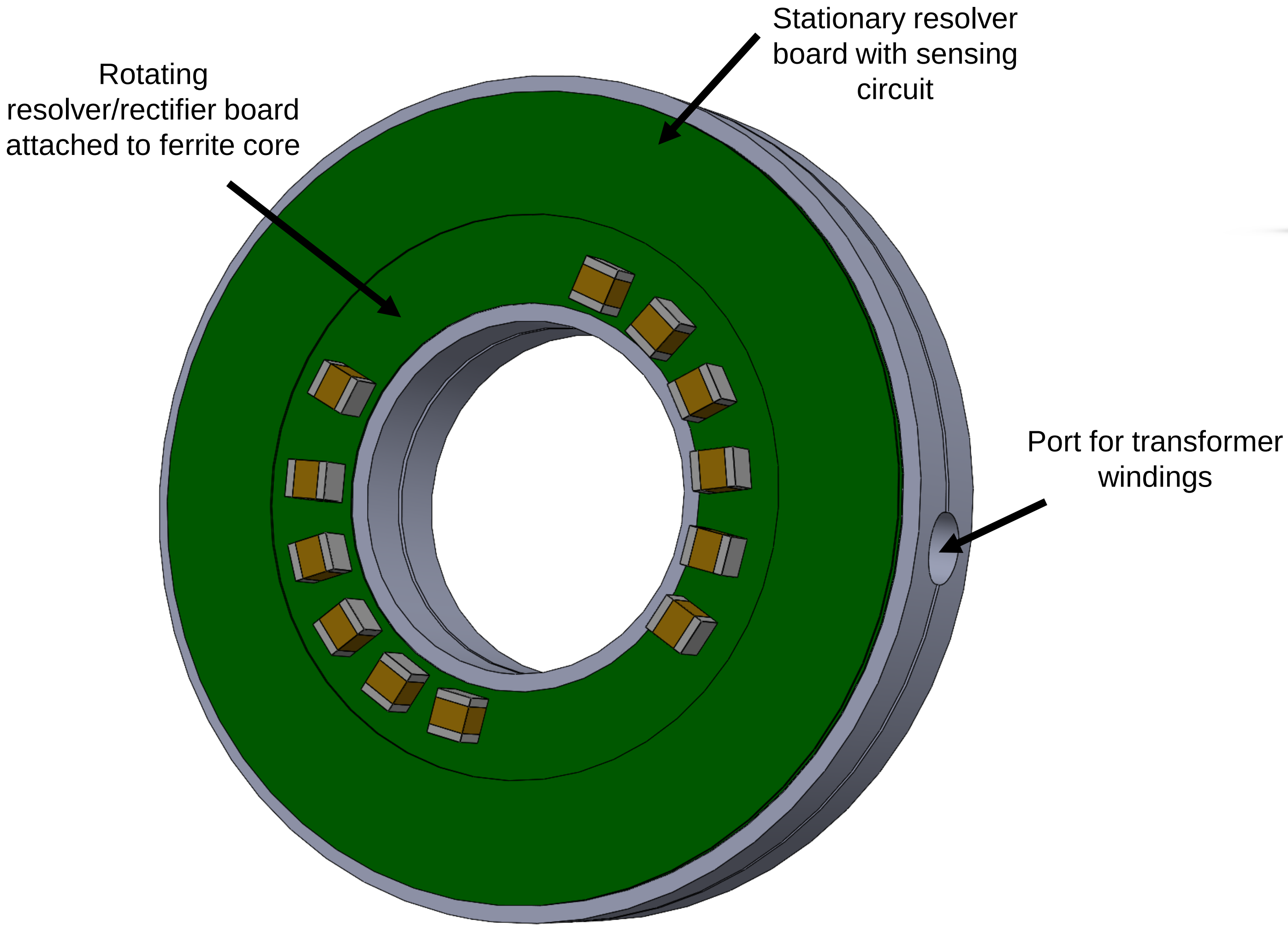


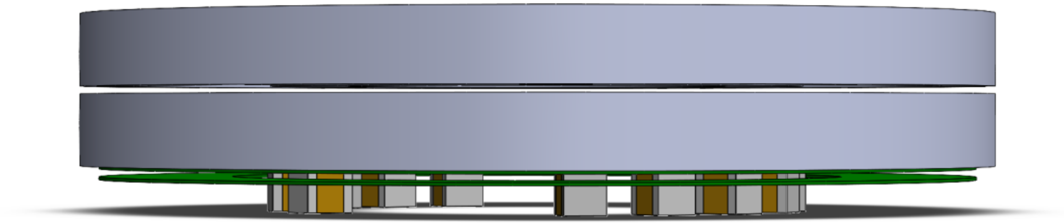


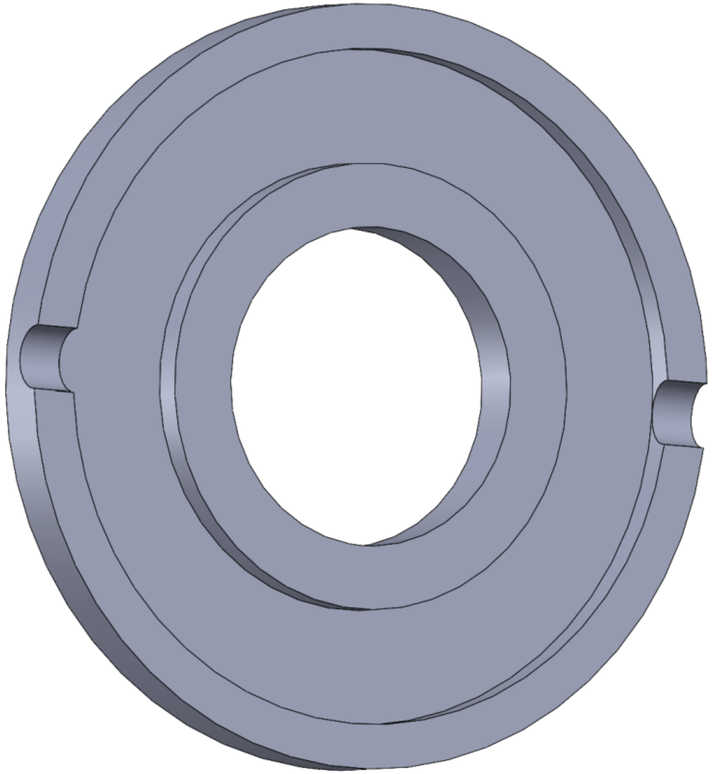
- Latest WFSM design is 7kW field (peak), demands IPT
  - CPT is reasonable for < 1.5 kW
- 100mm diameter rotary transformer
- Rectifier board incorporates capacitive resolver
  - Resolver comes “for free”
  - Uses surfaces on the rectifier board rather than windings
  - Decoupled from magnetic design/structure

Latest

Rotating Ferrite Transformer with Integrated Capacitive Resolver (7kW peak, 325 V, 30 kHz)







Rotary transformer notes

- Estimated mass ~1kg (accounting for ferrite and copper weight)
- Magnetizing inductance ~10mH, leakage of ~10uH, ~1:1 turns ratio
- Max operating power 7kW @ 325Vdc
- Estimated transformer efficiency 98-99% (estimated resistive copper losses and core losses)

Team Collaboration & Coordination

- Dr. Lakshmi Varaha Iyer of Magna International leads the technical team comprised of internal teams from Magna, Illinois Institute of Technology and University of Wisconsin-Madison led by Prof. Ian Brown and Prof. Dan Ludois respectively.

Weekly Virtual Project Meetings	Ongoing
Magna International	Cooling System Design Product & Manufacturing Requirements Testing and Reporting
University of Wisconsin-Madison	Rotor Excitation
Illinois Institute of Technology	WFSM Design and Prototyping

The roles of each participant are interdependent, frequent and effective communication is critical to the success of the program.

Market Impact and Sustainability

- An 8x increase in power density provides significant weight and packaging benefits to the powertrain leading to increased EV driving range.

- The use of copper for windings and steel for laminations enable significant cost reduction of the motor active material.

- Through the removal of rare earth permanent magnets, reduced concerns over environmental footprint and commercial availability.

- High power factor through field excitation control reducing the required size of the main traction inverter (compared to IPMSMs and IMs).

- Direct field weakening and large constant power speed range (CPSR) through field excitation control.

- Potential for improved safety through field control during inverter fault conditions (compared to IPMSMs)

Efficient use of Financial Resources

- Successful execution of a small $875,000 project, conducted over a 39-month project period by three recipients demands the efficient use of resources and execution according to the project plan.

- The opportunity to leverage the results of the past VTO-funded WFSM research effort, as well as the research team from IIT and UW-Madison significantly increases efficiency.

- Weekly project meetings are conducted via Teams maintaining the project focus relative to near- and long-term objectives, as well as a forum to present and address open issues in a timely manner.

Thank You

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